Jet Birth in Microquasar GRS 1915+105

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Abstract. We present simultaneous X-ray and radio views of accretion during jet outflow. Previously, we imaged superluminal ejecta after X-ray/radio flares, and discovered an AU-scale nuclear jet. Recently, we identified trends in RXTE ASM data to predict the flares, and so captured the evolution of the accretion disk with pointed PCA observations. We also observed in three radio bands with the VLBA on scales of 10-1000 AU, on 3 consecutive days.
The radio images show two distinct types of outflow, and the corresponding X-ray properties are clearly identified. We discuss the evolution of the disk/corona system (X-ray flux, spectral hardess, frequency of the 1-10 Hz QPO, and lag between fluctuations in the soft & hard bands) as the relativistic outflow is launched. We believe these X-ray/radio data represent strong constraints on models for the disk/jet connection. Considerable work remains, however, to decode the physical conditions operating in the disk from their observational signatures.

INTRODUCTION

GRS 1915+105 is a famous X-ray binary with superluminal ejecta [1], and spectacular X-ray variability from an unstable accretion disk [2, 3]. For nearly a decade, its nature was obscured by $A_\nu > 20$ at D$\sim$12 kpc. Finally, IR spectroscopy with the VLT [4] gave a mass of $14 \pm 4\ M_\odot$ for the primary, with companion of $\sim 1.2 \pm 0.2\ M_\odot$ in a 33.5 days orbit.

PREVIOUS OBSERVATIONS OF X-RAY STATES AND RADIO EMISSION

A few times per year, GRS 1915+105 emits radio flares of up to 1 Jy in superluminal ejecta. The large flare in 1992 [1] was monitored by the VLA with 200 milli arcsecond (mas) resolution. Both approaching and receding ejecta were detected, from which the inclination (70°), velocity ($\beta \sim 0.9$), optically thin spectrum ($S_\nu \sim \nu^{-0.6}$), and flux decay (e-fold in a few days) were determined. The mechanical power of the ejecta, $\sim 10^{39}$ergs/s, are comparable to the X-ray luminosity of the disk (see also [5]).

Our previous VLBA observations were triggered by Green Bank Interferometer radio monitoring. We imaged the ejecta a few days after flares [6], and measured apparent velocities of 1.4 c at $\sim$50 mas (600 AU), similar to those at 10,000 AU [7]. The VLBA images also revealed an AU-sized radio jet in the nucleus, which is steady before flares, and variable afterwards. The RXTE ASM light curves (Fig.1) evolve in a characteristic way, from the hard & steady 'plateau' state, through the flaring transition, to highly variable after a flare. The flares result in superluminal ejecta. On the other hand, the plateau state is always associated with the AU-size radio jet, and can last for weeks, emitting 10-100 mJy with a flat radio to IR spectrum [8, 9]. Integrated over time, the compact jet is as energetic as the radio flares, but less powerful. The low/hard state and AU jet are now believed to coexist in many X-ray binaries, though imaged in only a few [10]. Further, systems in the low/hard state often exhibit a strong QPO at a few Hz. The relation between radio emission and X-ray timing properties under steady conditions was explored in [11].

NEW OBSERVATIONS

The plateau and variable states are relatively long lived and well studied. In contrast, the accretion properties during the launch of ejecta were unobserved. Since we identifi ed trends in the ASM data, we could trigger observations *in anticipation* of a flare, and now have captured the transition from AU-scale jet to large-scale outflow. An overview of the observations is in Fig.1.

RXTE: PCA pointed scans were triggered, to study the accretion disk and hot electron corona via the x-ray

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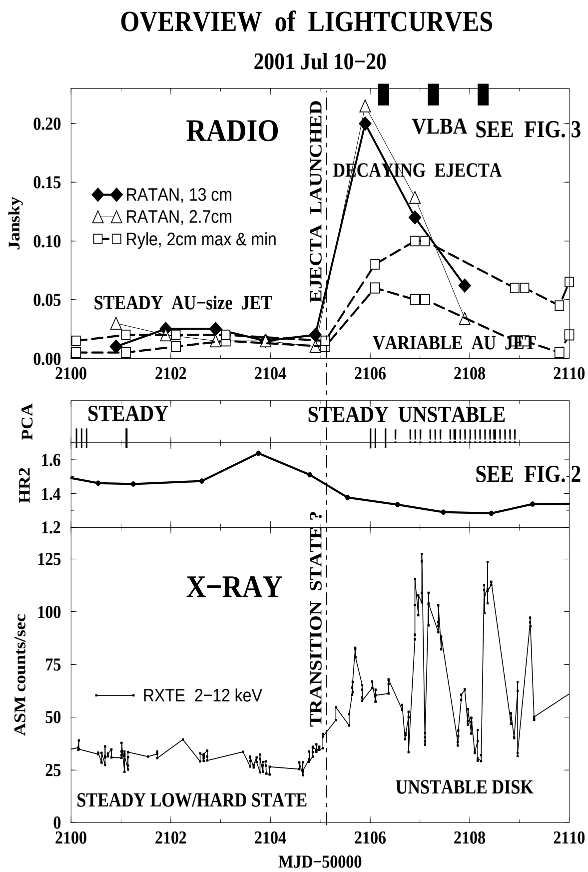

FIGURE 1. Transition from steady Low/Hard state via Flare (Ejection) to Oscillatory (variable) state. **Top:** Radio data with VLBA observations indicated by bars. **Bottom:** X-ray data with times of RXTE Proportional Counter Array scans. HR2: Hardness Ratio (10-20keV/2-6keV). ASM: RXTE All-Sky Monitor.

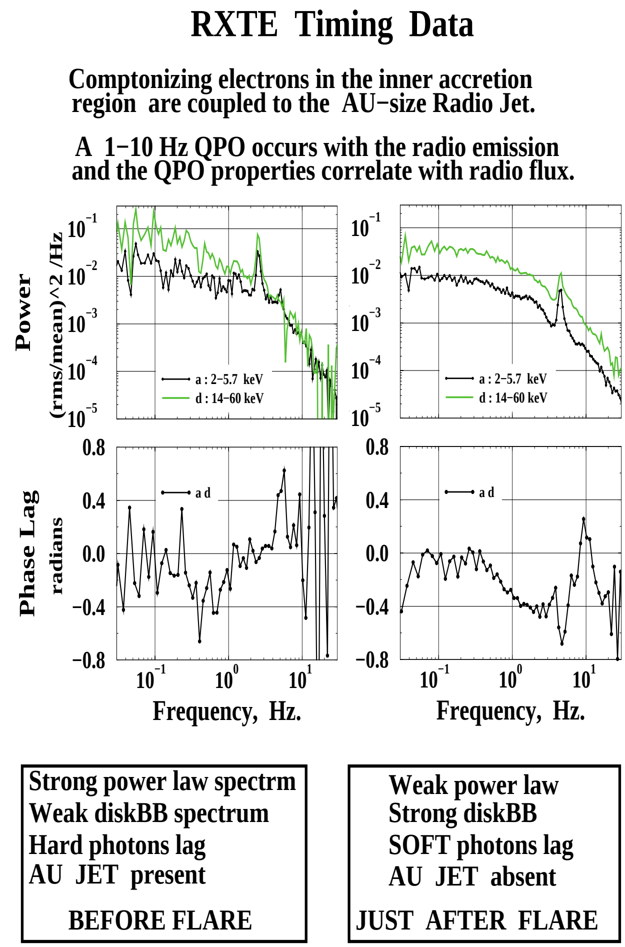

FIGURE 2. PCA auto & cross spectra of hard(10-20keV) and soft(2-6keV) fluctuations from 0.01-100Hz, indicate changes in the accretion disk and Comptonizing corona as ejecta are launched.

flux, hardness, and timing properties. For data reduction procedures see [11]. Fig. 2 shows selected PCA data, from the full sequence in Fig.1. There clearly are significant changes in the timing properties as the relativistic ejecta are launched. Compare **Before**, July 9 & 10, with AU jet present; and **After**, July 16, with AU jet ejected; also see images in Fig. 3. The 2-60keV spectra change as well (not shown; a detailed paper is in preparation).

VLBA: Five hours of recording at 256MB/s was used on each day, time shared equally between 13cm/3.6cm (50% bandwidth each) and 2cm. For data reduction see [6]. The observations times are shown in Fig. 1 (top). The images (Fig. 3) have absolute positions of 1 mas accuracy (3mas at 13cm).

RESULTS & CONCLUSIONS

1. We observe two types of radio emission: from moving, steep-spectrum ejecta; and from the immobile, AU-size, flat-spectrum jet. These may echo the FR I / FR II dichotomy in extragalactic radio sources.
2. Radio/X-ray flares occur as the disk/corona/jet system enters and exits the low/hard state. The exit flares are typically stronger; radio ‘cannonballs’ are ejected in either case.
3. Plasma is quasi-continuously ejected for ∼24hr, the length of the jet in Fig.2, X1. The rise time of big flares is about 6hr. This energy may accumulate over several days, shown by slow state changes before the flare, (but see next item).

4. The steady AU-jet exists in the low/hard state before the flare; it does not vent all the stored energy, despite time-averaged emission comparable to the flare.
5. The ejecta decouple from the disk in ∼1 d, then fade rapidly by adiabatic expansion (Fig. 2, X2, X3).
6. Shocks or modulations appear ∼200 AU downstream in the flow, and the continuous jet brightens at the leading edge. Despite this evidence for internal shocks in the ejecta, the primary motion is bulk displacement - plasma is seen to go from nucleus into ejecta. The distance of the leading edge from the nucleus is set by the elapsed time since the ejection, as in ballistic transport.
7. The AU jet disappears for ∼1 day after the ejection (July 16), but replenishes by July 17.
8. Disk & AU jet are steady before the ejection, and variable *after* recovery. There is no evidence for shocks in the variable state - the ejecta have departed (July 17, 18).
9. Timing properties: X-ray coherence evolves little over July 9-22 and resembles the radio-weak steady state. In contrast, hard X-ray phase lags change sign, *only* during the period when the AU jet is gone (July 16), and recover to their pre-flare state with the re-appearance of the jet. This key signature needs to be decoded. Is it caused by changes in Compton optical depth? Geometry? [12] Bulk relativistic velocity of jet plasma? Electron energy distribution? B-field reconnection [13]? Temperature?
10. Can the 'cannonball' and 'baby jet' outflows be unified? We compared the timing properties during:
    (a) the launch of superluminal ejecta, (here)
    (b) the 30 min flare/dip cycles, [9, 14],
    (c) various steady states, [11].
    Generally, the f_{QPO} positively correlated with count rate in all cases a, b, & c. Also, the coherence decreases progressively towards the harder bands; and the fractional rms fluctuation power increases in the harder bands. The two types of outflow evolve similarly in some X-ray properties, but their radio spectra, velocities, and decay times differ markedly.
11. A recent model for the disk/jet connection [15], predicts a rise time for the jet of about 10s, whereas we observe rise times of hours for the big flares. Even for the mini-flares in the AU-jet the rise time is ∼1000s.

We believe the sequence and timescales of these radio/X-ray data represent strong constraints on theoretical models. Standard accretion scenarios (∼1.5 keV disk, ∼60 keV corona) are challenged to fit the energy spectra, timing data, & images, together with high-γ electrons (200 MeV) in the jet, and the co-evolution of structures on disparate scales, viz. the inner disk (100 km), QPO-emitting region (10^5 km), and jet (10^9 km),.

In conclusion, we expect that high-quality data on more than a few sources will be required to resolve these issues. Enhancements to the sensitivity of the VLA by ∼10 are now funded, to be completed by 2009. Matching capabilities in All-Sky Monitors and X-ray timing are essential in our view.

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Radio images on 3 days at 3 wavelengths

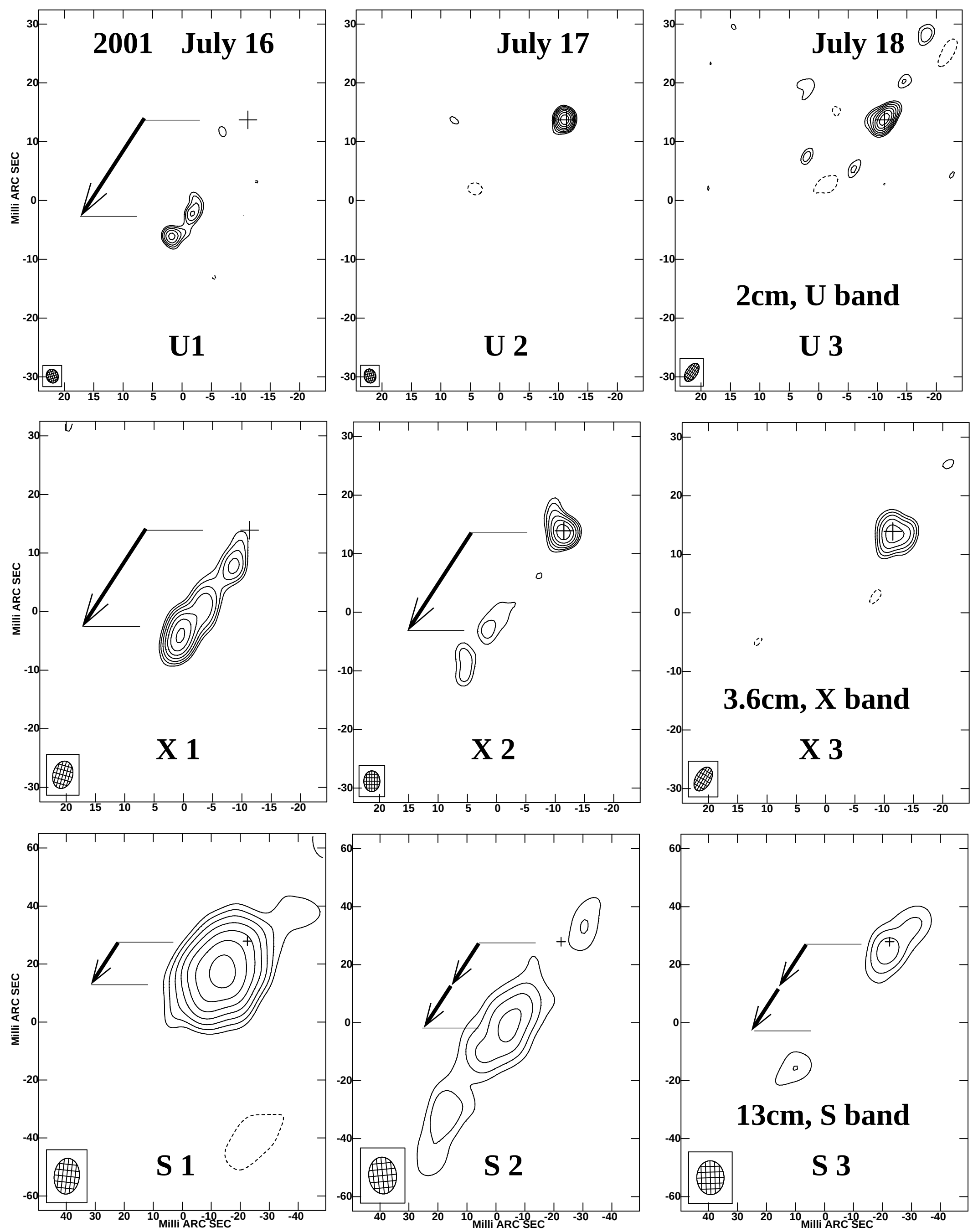

FIGURE 3. Note the optically thin ejection and absent core on Jul 16; and the replenished core & rapidly fading ejecta on July 17, 18. Only approaching ejecta are reliably detected. Contours start at ± 2 mJy/beam and step in multiples of 1.41. The cross ($\pm 3\sigma$) marks the same absolute position in each panel. Arrows are 20 mas = 240 AU = 24 hrs at 1.4c, the 'cannonical' speed of ejecta measured many times previously.